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Review on Recent Approaches for Hybrid PV/T Solar Technology

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Abstract-

This paper reviews the recent hybrid photovoltaic thermal (PV/T) structural/geometrical topologies to highlight the state-of-the-art on this form of collector approaches and designs for both liquid and air based systems. The review focuses on the development of the typical flat-plate collector - as an essential part in the PV/T system - in terms of new concept and novel configurations and specifically on the design of these collectors that use air or liquid as a heat transfer medium and their ability to extract useful heat from the back surface of the PV panel. Different mechanisms of fluid flow either natural or forced are considered. Many different design configurations for hybrid PV/T collectors have been catalogued and evaluated. It is shown that at least 30 distinct configurations have been introduced in the literature in the last five years. The paper concludes with identifying the major factors which affect the performance of typical PV/T systems and lead to effective enhancement of the heat removal mechanisms thus improving the electrical and thermal solar conversion efficiencies. This paper should serve as a significant form of reference for any future development in the design of the PV/T concept.

I. INTRODUCTION

The Energy Performance of Buildings Directive (EPBD) and Renewable Energy Framework Directive require that Renewable Energy Systems (RES) are actively promoted in offsetting conventional fossil fuel use in buildings. Integrating solar systems into the building elements (walls, roofs, etc.) not only means replacing a conventional building material (and associated costs) but also aesthetically integrating it into the building design leads to improved architectural integration. Two renewable energy technologies; photovoltaic and solar thermal collectors in separate or a combined format have been proven to be promising solutions in such situations [1-5].

The first integrated unit that combines hybrid components of solar thermal and photovoltaic technologies to yield dual functionality of heat and power from only one system is traced back to the mid-1970's [6]. The main concept in combining both elements was to remove the thermal energy that is produced during any photovoltaic operation resulting in a temperature rise and

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a corresponding decrease in its electric output. The combination of a thermal collector and a photovoltaic in a single system not only results in an increased efficiency of the total electrical solar energy conversion but also recovers some energy lost as heat.

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Many theoretical models [7-9] for such hybrid systems have been presented in the literature and experimentally verified. Studying the design factors that impact the behavior of the PV/T lead to design a range of PV/T systems that vary in structure, working phenomena and application. The number of PV/T configurations is broad and covers air, liquid collectors with and without concentrators where the used solar cell materials vary from mono and poly crystalline to amorphous silicon or thin-film. The PV panels are often assembled using glazed or unglazed frames and the heat transfer fluid flow is of natural or forced type. These configurations are usually integrated with building or utilized as an autonomous system. Simply stated the PV/T unit can be classified according to:

- Collector or absorber type
- Solar cell type
- Heat transfer mechanism
- Working fluid flow
- Application

It is noted in the literature that the PV/T of type flat plate can offer an alternative to conventional system for low-energy home applications, commercial and industrial premises. Given the large number of PV/T systems designs, a survey of the latest concepts methods would not only be beneficial to researchers and practitioners in PV/T systems but also can be considered as a step through the challenges that face the PV/T industry including the lack of common standards for collector design and testing. In fact so many methods have been developed that it has become difficult to adequately determine which method (new or existing) that is most appropriate for a given PV/T system.

This review provides a single point of reference that covers the most recently published material on PV/T state of the art from over 80 papers pertaining to different PV/T methods published over the last five years (2009-2014). It is not the intention of this review to establish a chronology of various designs and developments.

In this paper recent designs for regular PV/T collectors are surveyed. The aim of this study is to address the current modifications on the basic (typical) PV/T collectors and to provide a descriptive comparison between all of the surveyed designs. The review focuses on the design of the thermal part of the photovoltaic solar thermal unit with alternative designs, new topologies and novel configurations for air and liquid based flat plate PV/T systems being of particular interest. Hence any

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development for the photovoltaic part in terms of materials used or equipment added to the PV part such as concentrator and reflector are considered outside the scope of this paper.

This review considers a wide variety of PV/T designs providing a categorization with a brief discussion of the many PV/T systems currently available. The review catalogues details relating to the different PV/T system designs based on their thermal and electrical efficiencies, manufacturing aspects and applications. A comprehensive Table that summarizes the recent developments in PV/T design in terms of absorber structure, PV structure, working fluid, design parameters and electrical and thermal efficiencies are presented.

II. HYBRID PV/T SOLAR HEATER COLLECTOR

The heat that is normally associated with the photovoltaic effect in the solar cell can be harnessed and successfully used to raise the terminal output power of PV panels whilst also recovering panel heat extracted from the panels [10] that can be used to heat up space and water thereby improving overall PV/T system conversion efficiencies to more than 70% [10-12].

Although most of the solar insolation in the solar spectrum can be easily absorbed by PV cells, a small portion of this absorbed energy can only be used to produce electricity according to the PV cell conversion efficiency. The remaining portion of this absorbed energy is actually heating up the surface of the PV cell resulting in temperature increase that may lead to hot spots. This phenomenon affects the PV cell behavior and considered to be a detrimental issue that has serious consequence on reducing the cells' life time. So removing this accumulated heat is very important to ensure better PV cell performance particularly in the hot locations.

Significant research has been conducted to investigate different ways that can be utilized to give PV systems the required cooling arrangements. Amongst these ways PV/T units utilizing water/air coolant, heat pipes, thermoelectric instruments and materials that change its phase to assist decreasing the surface temperature of the PV cells have been developed [13].

Many water/air hybrid PV/T systems have been experimentally tested and inspected and the technology is considered to be mature [13-16]. Conversely the usage of heat pipe materials that change its phase and thermoelectric instruments to assist in either reducing PV cells' temperatures or producing heat still remain at the R&D phase. Although different techniques have been examined effective solutions have not been fixed for broad realization in large scale projects.

The following sections provide a comprehensive review of various designs of typical flat-plate Photovoltaic solar thermal systems in terms of concept, designs novelty, and recent configurations with an emphasis on BIPV/T which can be viewed as a crucial application area.

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A. Liquid collectors

In the climates characterized by high temperature air cooling alone can't provide heat extraction to reduce the PV cells temperature resulting in low conversion efficiencies.

Moreover the small heat capacity and low density of air precludes any progress in the dynamic behavior of air PV/T collectors and their wide spread use. In such situations liquid based PV/T is deemed to be a pretty substitute option to improve both the electrical and thermal performance efficiency [13, 14 , 17].

The typical design of the liquid based photovoltaic solar thermal collector normally consists of metallic slab and fluid channel absorber fixed to the rear of the photovoltaic cell and module. The fluid is either forced or gravity assisted to circulate through a series and parallel connected pipe configurations to permit effective transfer of heat from the PV to the working liquid [18-20].

Recently refrigerants have been used as working fluid in this type of PV/T systems adding phase change benefits to the operating mechanism [21].

Many design variations that use more novel developments for liquid PV/T systems are proposed in literature including modified serpentine absorber designs [22-23] and canister absorber designs [2 ,24].

A new integrated photovoltaic thermal collector unit [24] was proposed and aimed at increasing the overall output with less cost compared to conventional hybrid collectors. It consists of a monocrystalline PV module (UDTS50) that has a surface area of 0.425 m2 and the galvanized steel absorber mounted at the bottom part of the module and designed to use glycol liquid or air for cooling purposes. Fig. 1 is a simplified diagram of the proposed PV/T. Although the study provides numerical modelling and experimental validation of the proposed collector, it doesn't provide any comparison with other PV/T systems; moreover the proposed collector only permitted the coolant temperature to elevate by an average of 3°C difference in between inlet and outlet which is a very low temperature rise when compared to other similar devices.

Fig. 1 PV/T collector. (1: Tempered glass; 2: photovoltaic cells; 3: layer of Tedlar; 4: surface of the absorber; 5: exit opening of the coolant; 6: entry opening of the coolant; and 7: layer of insulation [24])

The experimental comparison of the proposed collector [24] with a traditional thermosyphon copper serpentine absorber was performed in [25] by Khaled Toufeka et al 2011, to investigate and measure the thermal and electrical behavior of both collectors. The study concludes that the new absorber integrated in the new collector with its given material and geometry not only improved the heat transfer to the fluid but also yielded a better thermal and electrical performance. It should be noted that this was only

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achieved for the case of no fluid circulation. Continuous fluid circulation didn't yield the same conclusion (refer to Fig. 6, 7 in [25]).

Touafek et al 2013 introduced an integrated photovoltaic thermal collector unit using a new galvanized steel absorber assembly that consisting of a plate and tubes format [22].

The heat exchanger and the proposed PV/T is shown in Fig. 2(a) whilst the complete unit is shown in Fig. 2(b).

Fig. 2 (a) Heat exchanger and PV/T & (b) The complete unit [22]

Three absorber configurations were designed in Fudholi [23] using continuous coil or configured tube consisting of one inlet and outlet to permit the heat transfer liquid (water) to get in and out the heat exchanger of the Fig. 3. It was found that with an increase in the mass flow rates, the electrical and thermal conversion efficiencies of the photovoltaic solar thermal water collector increased as correspondingly. Under 800 W/m^2 of solar radiation and a mass flow rate of 0.041 kg/s, the total efficiency was 65% for the spiral flow absorber design comprising 13% PV electric and 52% thermal.

Fig. 3 (a) Web flow absorber (b) direct flow absorber and (c) spiral flow absorber [23]

The absorber collector in Ciabattoni [26] constructed from metal plate with tubes for working fluid circulation had an. The electrical performance is improved by 6% greater than that of traditional PV module. They didn't provide any details about the thermal behavior of the proposed PV/T collector.

Daghigh et al 2011 in [27] use a simple aluminum plate with crystalline silicon and amorphous PV collectors subjected to Malaysia's humid and hot climatic conditions. The thermal and the combined PV/T efficiencies of the amorphous silicon based PV/T outperformed the crystalline silicon version at 72% and 77% compared to 51% and 63% respectively. The electrical efficiency for the amorphous modules was less than the crystalline 4.9% compared to 11.6%.

The conceptual design of a collector based on seven different design configurations is proposed in [28]. Some of these absorber designs have already been proposed and tested by previous investigator in [23]. The images of four absorbers are shown in Fig. 4. Investigation and comparison of these configurations determined that the spiral flow design was the most thermally efficient design with thermal efficiency at 50.12% and corresponding electrical efficiency of 11.98%.

Fig. 4 The conceptual design of the proposed four collectors (a) Oscillatory Flow Design (b) Serpentine Flow Design (c) Parallel-Serpentine Flow Design and (d) Modified Serpentine-Parallel Flow Design [27]

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Bambrook [29] investigated an arrangement of PV/T insulation for a liquid collector. The study concludes that the insulation in the PV/T system increases the thermal performance of the PV/T by 6.7% while maintaining the same PV electrical performance.

The PV/T system designed by Mohammed [30] aimed at achieving a low cost unit with high electrical and thermal outputs by utilizing typical system components that combined a polypropylene heating absorber with a commercial photovoltaic system. The use of polypropylene had three main features compared to typical absorber materials such as aluminum and copper: it is corrosion proof, the cost of the material is low and the absorber is relatively agile.

Gang [31] proposed a new photovoltaic thermal system with heat pipe as shown in Fig. 5 that could jointly provide heat and electrical energy to overcome the water freezing problem that may lead to failure of the PV/T collector. Recently this approach which basically permits heat transfer almost without any temperature loss and hence eliminating freezing and reducing corrosion is well adopted in many studies [32, 33] for a practical design of a PV/T collector.

Fig. 5 The Heat Pipe PV/T solar collector [31]

A tube and sheet thermal collector (type A) is evaluated by Dubey [34] with a parallel plate channel type thermal collector (type B) (Fig. 6). It is reported that type B is suitable for low pressure (1–3 bar) applications whilst type A can be used for high pressure applications (up to 10 bar). An increase of 0.4% in the average PV efficiency due to cooling from the circulating water was achieved for the PV/T compared to their corresponding standard PV modules.

Fig. 6 cross-sectional view of (a) type A PV/T module (b) type B PV/T module [34]

A novel PV/T system design was introduced and simulated by Ziapou in [35]. The proposed system was an improved collector solar thermal water heating system integrated with a PV solar system. The study evaluated the impacts of the water tank mass the packaging factor of the PV cell and the area of the collector on the behavior of the proposed PV/T system. It is concluded that the efficiency of such system is increased when raising both the packing factor of the PV cell and the mass of the water tank. Conversely the system conversion efficiency declined with increasing collector surface area.

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B. Air collectors

According to Zondag [36] the history of the air based PV/T collector can be tracked back to the work carried out by Malik [15,37], a PV/T facility consisted of 24 roof collectors equipped with CdS/Cu_2S cells were constructed at the University of Delaware in the first half of the 70's. The air collectors provided a simple cost effective solution for PV cooling and could be used in various applications across a range of operating temperature with either forced or natural flow [38].

Generally research on PV/T air type systems depends on two generic formats; Flat plate air based PV/T collectors mounted on buildings and building integrated PV/T system used primarily in warm air ventilation systems. Different topologies and configurations **of** these systems are rigorously studied and analyzed in the literature. Hegazy [16] studied four models based on air flow paths: on the top of the absorber (model I), beneath the absorber (model II), on both sides of the absorber as single pass (model III) and double pass (model IV). The results indicated that models III and IV are the best in terms of their overall performance while Model I collector exhibits minimum overall behavior. Moreover the study reflected the importance of the mass flow rate in determining the overall behavior of such models. Other adaptations are implemented with single and double glazed configurations [39]. Many different design parameters and factors that affect the performance of collectors are the glass to glass or glass to tedlar type PV configurations in [40,41], the climatic conditions [42,43], semi-transparent hybrid PV/T single pass and double pass air collector [44], air flow rate, heat removal and fill factor [45]. An attempt to survey the very recent topologies and configurations of the air type of PV/T system is presented in the following section.

Air type coolant PV/T is used in [45] instead of water type used in [46] but with the same configuration. A one day test is only performed to check the behavior of the proposed PV/T. The paper didn't provide any information about neither the thickness of the proposed air observer nor for the air flow rate which are very important in the design of air based hybrid collector.

Rajoria et al [47] have analyzed the overall thermal energy and exergy for several topologies of air based hybrid photovoltaic thermal systems. The generic system consisted of an air type PV/T array (10.08 m x 2.16 m) having number of photovoltaic modules equal to 36 (glass to tedlar) and each module (1.12 m x 0.54 m) included 36 solar cells. Four configurations of array were considered. A standard layout of the hybrid PV/T array presenting flow configuration for case-I including expanded view of the PV module and its total sectional view is shown in Fig. 7. Although case-II gave better outcomes in terms of total thermal energy yield configuration under case-III was a better choice in comparison to other cases due to high grade of energy.

Fig. 7 Standard layout of hybrid PV/T array presenting flow configuration case-I with an expanded view of the PV module and its total sectional view [47]

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Agrawal and Tiwari [48] built on the work presented by Rajoria [47] and introduced a slightly different structure to the PV/T unit where a micro-channel encapsulated in between the solar cell and tedlar layer as shown in Fig. 8(a). Unlike the traditional PV module where the tedlar thermal resistance is found in between the PV module and flowing air, the thermal resistance of the tedlar in this PV/T design is eliminated. A combined micro-channel photovoltaic thermal module (Fig. 8(b)) was considered and the total annual yield in energy, exergy and exergy efficiency of the micro-channel photovoltaic thermal module were investigated under four kinds of climatic conditions in four distinct cities in India.

Fig. 8 (a) proposed micro-channel PV/T unit and (b) micro-channel PV/T module [48]

A modification of the work presented in Agrawa et al 2011 [48] has been found in Matuska [50] where a glazed hybrid micro-channel PV/T is designed. The electrical and thermal performance of glazed micro channel PV/T was significantly higher than the single channel PV/T. A novel glazed PV/T collector concept based on PV laminate with siloxane gel is now under development at Czech Technical University in Prague. Siloxane gel instead of Ethylene-vinyl acetate (EVA) lamination compound offers several important advantages such as high temperature resistance, high transparency, compensation of thermal dilatation stresses and good heat transfer from the photovoltaic to the heat exchanger in photovoltaic thermal collectors [51].

The tile based air type PV/T module [49] was compared with the study carried out by Agrawal [48]. The enviro-economic parameter and carbon dioxide mitigation were assessed and compared based on the calculated exergy and energy gain for various environmental conditions of India.

Bambrook [29] report upon an unglazed single pass open loop PV/T air system designed and experimentally tested in Sydney Australia. In the proposed PV/T an energy efficient hydraulic design using large pipes to reduce pressure loss and permit selection of a fan that would produce high air flow rates with minimum power input was utilized. The experimental PV/T air system in this study demonstrated increased electrical and thermal photovoltaic efficiencies with rising up the flow rate of air mass. At midday the electrical and thermal efficiencies were recorded to be in the range of 10.6% and 12.2% and 28 to 55% respectively.

A wooden duct mounted to a 75 W monocrystalline photovoltaic silicon panel permits air to pass beneath the photovoltaic module to capture heat energy from the PV back surface [52]. A platform made from steel is integrated permitting movement including a small DC fan (1.5 A and 12 volt) to create an air flow that alter the mass flow rate through variable resistance.

Different conceptual designs of air based hybrid PV/T collectors are presented and analyzed by Amori and Abd-ALRaheem [53]. The main focus of this work was to enhance the cooling mechanism used by solar modules in order to reduce the operating cell temperature and to improve the thermal efficiency of the collector. Three PV/T configurations were developed and compared

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with two reference PV modules connected in parallel without cooling. The first PV/T model where air flows in a channel established between the PV module and the glass cover is directed to a second channel in between the back of the copper plate and PV modules as shown in Fig. 9(a). In the second PV/T model (Fig. 9(b)) air flows in two ducts above and below the PV module in the same direction whilst in model three air passes in a single duct beneath the absorber only (Fig. 9(c)). The obtained results show that the combined efficiency of the collector in the second model is more than that of the first model and third model. The third model has the best electrical efficiency. The pressure drop in the second model is less than in the first and third models.

Fig. 9 Experimental setup schematic diagram of the a) first model b) second model and c) third model [53]

A similar double pass air collector concept is utilized in [55-58] where air flows in opposite directions in the ducts and the performance is compared to a single pass air collector [55]. Fig. 10 depicts a schematic of the proposed system with the two PV modules wired together in series connection and placed on a wooden frame that is rectangular in shape. The lower and the upper ducts are formed between the upper glass and the PV module and the below duct is created below the PV module. The air flowing in each duct flow in opposite directions with equal cross sectional area for both ducts to allow maintain an equal air velocity. In order to maximize solar irradiance the whole system mounted in a steel frame that can be inclined to optimize the solar collector angle. Air flow is provided through DC fan.

Fig. 10 (a) Cross section of the single-pass HPV/T air collector and (b) schematic diagram of the double-pass HPV/T air collector [54]

Fig. 11 shows three different air based PV/T collector designs recently proposed by Alfegi et al 2009 [59]. The designs are based around V-groove, honeycomb and stainless steel wool horizontal channels placed at back side of a PV module. The most promising heat exchanger design and PV arrangement is the honeycomb design which yields a maximum overall efficiency of 94.13%. The design is simple and compact and is relevant for building integration.

Fig. 11 PV modules with several designs of heat exchanger (a) honeycomb (b) V-groove (c) stainless steel wool [59]

A novel design consisting of a single pass double duct PV/T with fins is studied by Jin [60]. The PV/T efficiency increased from 49.13% to 62.82% at changing mass flow rates from 0.0316 to 0.09 kg/s respectively, solar insolation at 600 W/m^2 and an inlet temperature of 35 °C.

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A single pass PV/T air collector with rectangle tunnel absorber was developed by Chow [61]. The proposed rectangle tunnel provided an absorbing element fixed beneath the photovoltaic panel. Results show that the hybrid PV/T with rectangle tunnel gave a higher performance in terms of combined PV/T efficiency of 64.72% and thermal efficiency at 54.70% with solar insolation of 817.4Wm^{-2} and mass flow rate of 0.0287 kg s^{-1} at ambient temperature of 25 °C compared to a traditional PV/T system.

C. BIPV/T system

At the start of the 1990s large photovoltaic facades begin to receive attention and their ventilation/cooling to reduce the PV temperatures resulted in this heat being collected for building heating applications. However the tied space available to accommodate multiple solar devices has led to the use of hybrid solar system for the cogeneration of electricity and heat. This is also driven recently by increasing interest in the development of low-carbon zero-energy buildings [62].

A flat-box thermal absorber for a building-integrated application is proposed by Chow et al [63] using water based photovoltaic thermal designs. The yearly energy performance characteristics of the proposed integrated solar system have been identified by the aid of numerical models and experimentally validated data. Over one year the thermal energy gains for forced and natural modes of circulation are 965 MJ/m^2 and 1011 MJ/m^2 respectively and the electrical energy gains excluding pump energy consumption are 239 MJ/m^2 and 167 MJ/m^2 respectively based on the unit area of the PV module.

A novel BIPV/T air collector is presented by Tsai [42] where it is augmented with a fin –type heat sink with a large ratio of depth to spacing width is coated with ALO_3 insulating film exhibiting a high thermal conductivity (Fig. 12). These fins are attached at the rear of troughed BIPV module with the back wall having the same space to the tips of fins. The PV/T air collector is assembled in layers of laminated PV pre-treated heat absorber with heat sink and thermal insulation. The results of BIPV/T air collector performance evaluation reveals that an efficiency of 56% can be achieved.

Fig. 12 BIPV/T air collector [42]

An open-loop unglazed transpired collector (UTC) consisting of dark porous coating where the outdoor air can be pulled and heated by incident solar insolation is combined with PV modules to operate as BIPV/T [64]. The system was successfully utilized to heat air in winter whilst producing electric energy from the same building envelope surface. The design was based on a black-framed PV module specifically designed to improve the absorbed solar energy and heat recovery attached to a horizontally corrugated UTC. Air is trapped within the gab in between the UTC & the panels and is directed into a UTC plenum. The concept was applied and validated within an office premise in Canada.

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A different building integrated PV/T system is examined by Zondag [65]. The proposed system utilizes a troughed sheet roof which is made from aluminum or plated steel. It is rolled in such a way that provides the roof stiffness strength and when collected together weather proofing. This system uses materials with high level of thermal conductivity to form the building integrated PV/T collector. The trough is equipped with channels in which the thermal cooling medium travels through. The PV cells are laminated and bonded onto the trough. The channels are subsequently surrounded by the cover; thus creating a path where the heat can be conveyed and transferred. Inlet and an outlet are at counter directions of the trough as shown in Fig. 13.

Fig. 13 BIPV/T collector [65]

III. Discussion

With so many PV/T designs available it wholly possible that the correct design may not always be matched to the most appropriate application. The main challenges for the PV/T liquid and air collector selection are addressed in the following subsections.

A. Manufacturing

The most recent techniques to manufacture typical flat plate PV/T collectors shown in Table I is to establish a form of channel just beneath an encapsulated PV module of type crystalline silicon with a suitable depth and actively/passively circulate water/air in that spacing to work as heat transfer fluid. The enclosure is commonly made from Galvanized steel [1, 2, 4], stainless steel [5, 11] or wood type as in [53]. Sometimes PV/T's are manufactured by gluing either solar cells or complete commercial PV laminates to the thermal absorber of a pre-existing collector unit [25, 23]. This encompasses two problems as mentioned by Zondage [36] where the large thermal resistance of such unit will hinder good thermal performance and relatively large reflection losses may occur in crystalline silicon type modules. A more advanced lamination technique specifically (with care given to electrical insulation) should be used. Moreover the encapsulate should be able to resist the high temperatures that happen in stagnating glazed PV/T modules which can be as high as 130°C [66]. Good PV optical characteristics are also an important factor.

B. Thermal module efficiency

The thermal module efficiency can attain high values (above 85%) using special configured design such as honeycomb channels or stainless steel wool channels located behind the PV module [59]. A V groove cavity at the back surface of the PV module and aluminum plates for the absorber structure can also increase the thermal efficiency to above 70%. A moderate value of thermal efficiency can be reached using galvanized steel enclosure absorbers with a reasonable discrepancy for the type of the heat transfer fluid. Increasing the flow rate of the fluid enhances the thermal behavior of the module especially with the air type

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collector [59]. Using top glazing is also a very effective means to obtain strong increase in thermal performance for liquid and air PV/T collectors. The following factors; reflection loss, spectral selectivity and thermal resistance are suggested and well discussed [16] and [36] to indicate the thermal loss mechanisms in the PV/T collector. Diverse techniques have been proposed in the literature to reduce long-wavelength radiation reflection by the PV. The silicon texturing to minimize reflection [67-70] has been taken more attention.

C. Electrical module efficiency

Generally speaking the thermal system design for a certain application can have positive or negative impact on the PV power output depending on the system dimension and the temperature of the PV/T absorber. Other design factors can also affect the electrical module efficiency. The types of the solar cell shading, temperature effect & homogeneity and cover reflection are some of the factors affecting the electrical efficiency of PV/T collectors. For example in [25] the electrical efficiency of a polycrystalline PV laminated sheet reached to 14% for the PV/T collector of air type while the thermal design of stainless steel wool channel located at the back side of the PV module suggested in [59] that the thermal module efficiency may go up to 86% on the account of low electrical module efficiency 6.88% for a monocrystalline PV module. Shading part of the absorber in solar thermal conventional collectors may not affect the performance significantly likewise in case of PV/T unit. This real condition can cause a great degradation for the output power from PV module even if it happens for only one cell of the entire module.

D. Application

Over the past 40 years the domestic and the industrial applications that based on the PV/T flat plate collectors were heavily developed either for glazed or unglazed collectors.

In PV/T applications producing heated water is handier than producing warm air for space heating. Therefore hot water PV/T systems have been applied in domestic, commercial and industrial buildings, especially in humid and hot environments where space heating not required [17]. PV/T liquid collectors show good heat usability in low temperature applications such as heat pumps primary circuits (0 to 10 °C), pool water heating (25 to 35 °C), household hot water and space heating (up to 60 °C).

PV/T air cooled and solar collectors have already been utilized for products drying in solar and solar assisted heat pump drying technologies. BIPVT usage are in between the cost effective solar energy applications when solar radiation incident on a façade of the building is directly transformed into beneficial electric and thermal power, the fraction of solar energy transmitted through the building envelope is reduced. Hence the space cooling demand is decreased. Conversely a building façade dominated by crystalline silicon solar cells in a dark blue color can share the same aesthetical impact as in building integrated PV system. It was shown that by integrating the PV/T *into* the building rather than *onto* the building could yield a lower cost system [71, 72]. Many commercial products and engineering projects already exist in different countries and PV/T systems are applied as

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preheat ventilation air [73] ventilation supplementary heating and air dehumidification project [74] and heating operating agricultural drying process [75].

More recently new areas of application that based on self-sustainable design of PV/T; Solar distillation of brackish water to obtain fresh water [76] sustainable reverse osmosis (RO) desalination [77], crop drying [78,79] have gained more attention. For instance, Fudholi et al. [79] showed that drying products such as agricultural and marine one are deemed to be the most attractive and cost effective applications for solar energy.

Design steps as well as dynamic simulation of a new solar tri-generation system based on integrated photovoltaic thermal collectors are presented by Calisea [80]. The behavioural study of the proposed system show that the system can be profitable and the total energetic and economic outcomes are comparable to those mentioned in literature for analogous systems. The experimental investigation on operational behaviours of a photovoltaic–thermal solar heat pump for air-conditioning application is carried out by Fang [81]. A significant enhancement in electrical and thermal efficiencies is achieved by Zhao [82] using novel design of PV/T as a roof module. It is a roof element electricity generator and the evaporator of a heat pump system that can achieve considerable enhancement in electrical and thermal efficiencies

E. Cost

The cost of PV/T systems is higher than the cost of standard PV modules because of the additional of the thermal unit. PV/T systems could be cost effective if the additional thermal components' cost is low and the extracted heat is effectively utilized. The economic viability of different configurations of PV/T systems have been checked in different studies in the literature [83, 84]. The economic analysis and the cost consideration in these studies reveal that PV/T economic viability depends upon the primary cost and the magnitude of energy (electrical & thermal) that can be gained from such systems. Kalogirou and Tripanagnostopoulos [83] emphasis that a life cycle analysis is a vital tool to get the overall cost (or life cycle cost) and the life cycle savings of the systems. The thermal load and auxiliary energy required play essential role in determining the first year fuel savings and the solar system cost. The investment cost of the solar system is valued by considering the present cost of the different parts of the systems (heat extraction unit, PV module, inverter, pump, pipes, cables, the storage tank,… etc.). The operating cost, maintenance and parasitic costs should be taken into consideration.

Different two hybrid PV/T systems, one with pc-Si and the other one is a-Si PV type were constructed and tested by Kalogirou and Tripanagnostopoulos [83] at three locations in Greece. The payback times (in years) of each system studied are calculated and compared with PV system alone reflecting the merit of the hybrid PV/T systems over the PV system as much shorter times are indicated. By comparing the polycrystalline and the amorphous silicon cells the latter were seen to be slightly better for the hybrid PV/T as they have better cost benefit ratios.

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The cost per kWh and payback time of grid-tied photovoltaic system joined with a solar system for heating water at four different places in New Zealand is studied by Abdalla [84]. The energy cost in New Zealand dollar versus the system life time is illustrated the relationship between the payback time of the suggested system at various places and the energy prices is described (refer to Fig. 3 and 5 in [84]). It can be concluded that the payback time of the proposed PV/T system get shorter as the benefits of the system get higher when the energy prices at the site of operation get higher.

IV. Conclusion

Better utilization of solar energy and a higher overall solar conversion rate can be realized by using PV/T systems. The ability for single product to offer dual functionality in a unique modular design presents great commercial opportunity and makes its market potential very high over the singular PV and solar thermal systems. Several PV/T designs taken from literature are discussed and analyzed in this paper. The review work above reveals that special design are essential for improving the behavior of PV/T systems according to the followings factors: (1) air/water flow channels/ducts geometry and sizes; (2) air/water flow velocity and temperature; (3) PV type and corresponding climate (4) air/air heat exchanger in air based systems; (5) active fan in air based systems; (6) selecting proper glazing mode (covered/uncovered with single/double glass). Conversely problems such as low density, specific heat capacity and thermal conductivity of air based systems and/or freezing in colder climatic regions and additional pre-heating thus increasing complexity for the water based systems may lead to poor heat removal and a lower overall efficiency. Although the research conducted on PV/T systems is detailed there is still further scope for improvement on PVT technology. Finally the concluding discussion and the Table I should serve as a useful guide in checking the recent advances in two typical types of PV/T systems in terms of different designs and novel configurations.

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Figures' captions

Fig. 1 PV/T collector. (1: Tempered glass; 2: photovoltaic cells; 3: layer of Tedlar; 4: surface of the absorber; 5: exit opening of the coolant; 6: entry opening of the coolant; and 7: layer of insulation [24])

Fig. 2 (a) Heat exchanger and PV/T & (b) The complete unit [22]

Fig. 3 (a) Web flow absorber (b) direct flow absorber and (c) spiral flow absorber [23]

Fig. 4 The conceptual design of the proposed four collectors (a) Oscillatory Flow Design (b) Serpentine Flow Design (c) Parallel-Serpentine Flow Design and (d) Modified Serpentine-Parallel Flow Design [27]

Fig. 5 The Heat Pipe PV/T solar collector [31]

Fig. 6 cross-sectional view of (a) type A PV/T module (b) type B PV/T module [34]

Fig. 7 Standard layout of hybrid PV/T array presenting flow configuration case-I with an expanded view of the PV module and its total sectional view [47]

Fig. 8 (a) proposed micro-channel PV/T unit and (b) micro-channel PV/T module [48]

Fig. 9 Experimental setup schematic diagram of the a) first model b) second model and c) third model [53]

Fig. 10 (a) Cross section of the single-pass HPV/T air collector and (b) schematic diagram of the double-pass HPV/T air collector [54]

Fig. 11 PV modules with several designs of heat exchanger (a) honeycomb (b) V-groove (c) stainless steel wool [59]

Fig. 12 BIPV/T air collector [42]

Fig. 13 BIPV/T collector [65]

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Table I Recent flat plate PVT collector

Absorber Structure	**Photovoltaic Structure**			**Working Fluid**	**Operating Conditions**			**Efficiency %**			**Ref.**
	Type	cell	Module		Kg/s	W/m^2	°C	PV	T	PV/T	
Galvanized Steel Enclosure	Mono -crystal	---	Module	Water	NA	NA	NA	11	69	80	[1]
Galvanized Steel Canister	Mono -crystal	---	Module	Water	NA	NA	NA	NA	NA	NA	[2]
Copper Serpentine	Mono -crystal	---	Module	Water	NA	NA	NA	NA	NA	NA	[2]
Galvanized Steel Plate (tank) + Galvanized Steel Tube	Mono -crystal	---	Module	Water	NA	NA	NA	NA	NA	NA	[3]
Galvanized Steel Enclosure	Mono -crystal	---	Module	Air	NA	NA	NA	NA	48	N/P	[4]
Spiral Stainless Steel Tube	Poly -crystal	Lam. Sheet	---	Water	NA	NA	NA	13	52	65,69	[5], [8]
Web Stainless Steel Tube	Poly -crystal	Lam. Sheet	---	Water	NA	NA	NA	NA	NA	NA, 55.2	[5], [11]
Direct Flow Rectangle Stainless Steel Tube	Poly -crystal	Lam. Sheet	---	Water	0.01	NA	NA	NA	NA	NA, 59	[5], [11]
Metal Plate + Circulating Tubes	Poly -crystal	---	Module	Water	NA	NA	NA	10.06	NA	NA	[6]
Aluminum Plates	Amor.	---	Module	Water	0.02	700-900	22-32	4.9	72	77	[10]
Aluminum Plates	Crystal.	---	Module	Water	0.02	700-900	22-32	11.6	51	63	[10]
Oscillatory Flow Design	Poly-crystal	Lam. Sheet	---	Water	0.01	NA	NA	NA	NA	55	[11]
Parallel Serpentine Flow Design	Poly-crystal	Lam. Sheet	---	Water	0.01	NA	NA	NA	NA	63	[11]
Modified Serpentine-Parallel Flow Design	Poly-crystal	Lam. Sheet	---	Water	0.01	NA	NA	NA	NA	63.2	[11]
Flat Box Type	Poly-crystal			Water	0.013	800	NA	9.39	37.5	46.89	[12]
Air Circulated Flat Canister	NA	---	Module	Air	0.0019	NA	NA	NA	NA	NA	[47] [11]
Shallow Rectangular Insulated Duct (thick extruded polystyrene) Sandwiched Between Galvanized Steel Sheets.	Mono -crystal	---	Module	Air	0.03–0.05	NA	NA	10.6 12.2	28 55	38.6 67.2	[22]
Web Flow Absorber, Direct Flow Absorber and Spiral Flow Absorber.	Poly-crystal	Lam. Sheet	---	Water	NA	1000	25	14	52	65	[23]
Fully and Partially Insulated Serpentine	Mono -crystal	---	Module	Water	0.5	800	NA	13	27	40	[27]
one cover glazing, the solar cell, the absorber plate, the insulation box and the storage unit with two improved trapezoids cross section duct.	Poly-crystal	---	Module	Water	NA	400-850	45.9	12.55	36.1	48.7	[29]
A wooden Duct with	Mono	---	Module	Air	0.01	600	38	8.4	42	50	[36]

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	-crystal										
Honeycomb Channel located at the Back Side of the PV Module	Mono -crystal	---	Module	Air	0.11	828	NA	7.13	87	94.1	[59]
V Groove Channel located at the Back Side of the PV Module	Mono -crystal	---	Module	Air	0.11	828	NA	7.04	71	78.04	[59]
Stainless Steel Wool Channel located at the Back Side of the PV Module	Mono -crystal	---	Module	Air	0.11	828	NA	6.88	86	92.88	[59]
Parallel-Plate Type Thermal Collector	Poly-crystal	---	Module	Water	0.06	400-850	NA	11.5	39.4	50.9	
Single Pass PV/T with Finned of Double Duct PV/T Air Heaters	NA	NA	NA	Air	0.0316 - 0.09	600 W	35	NA	NA	62.8 - 49.1	[60]
Single Pass PV/T With Rectangular Tunnel Design	NA	---	Module	Air	0.0287	817.4	25	10	54.7	64.7	[61]

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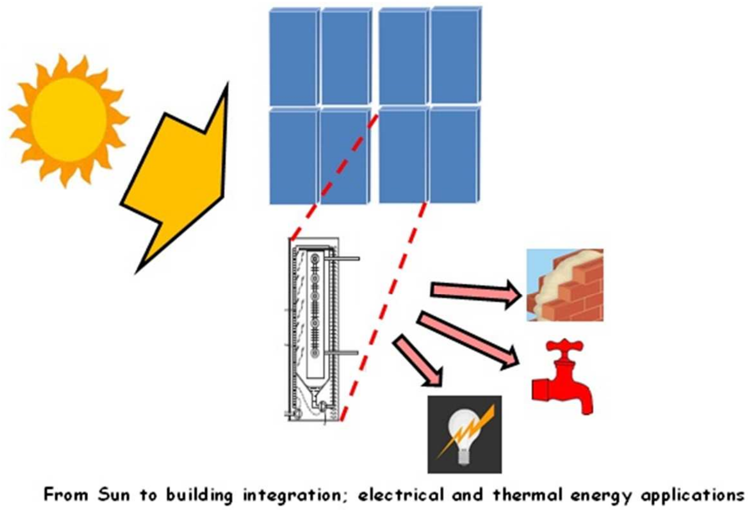
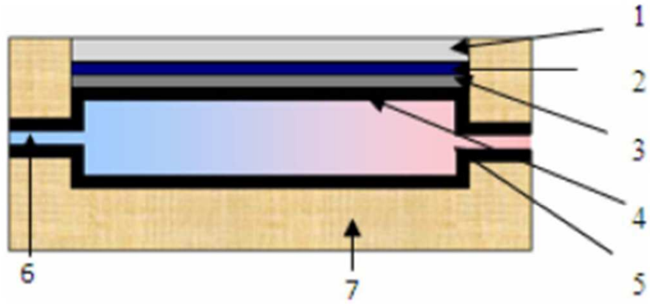


203x127mm (96 x 96 DPI)

Review



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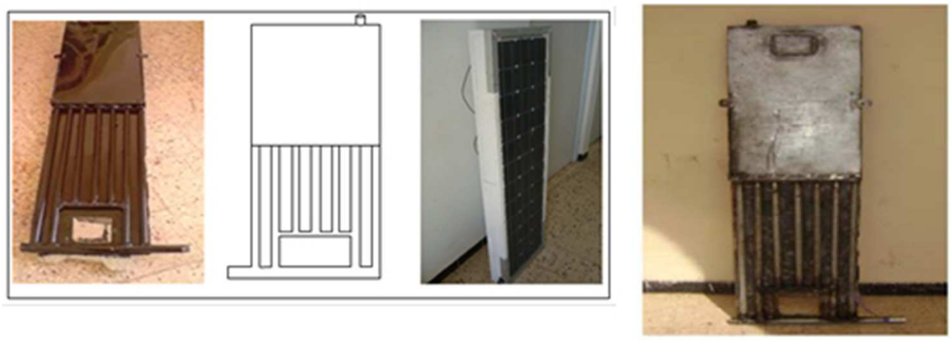

(a) (b)

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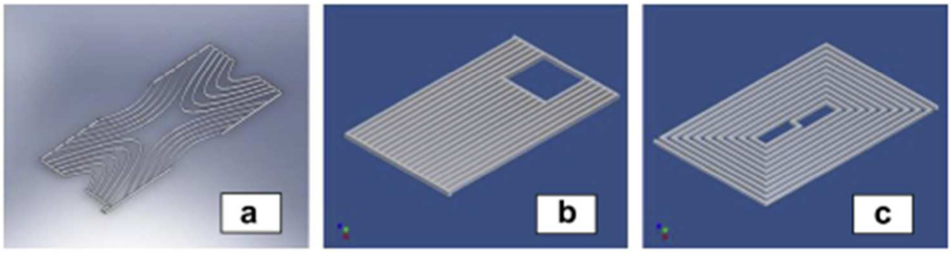

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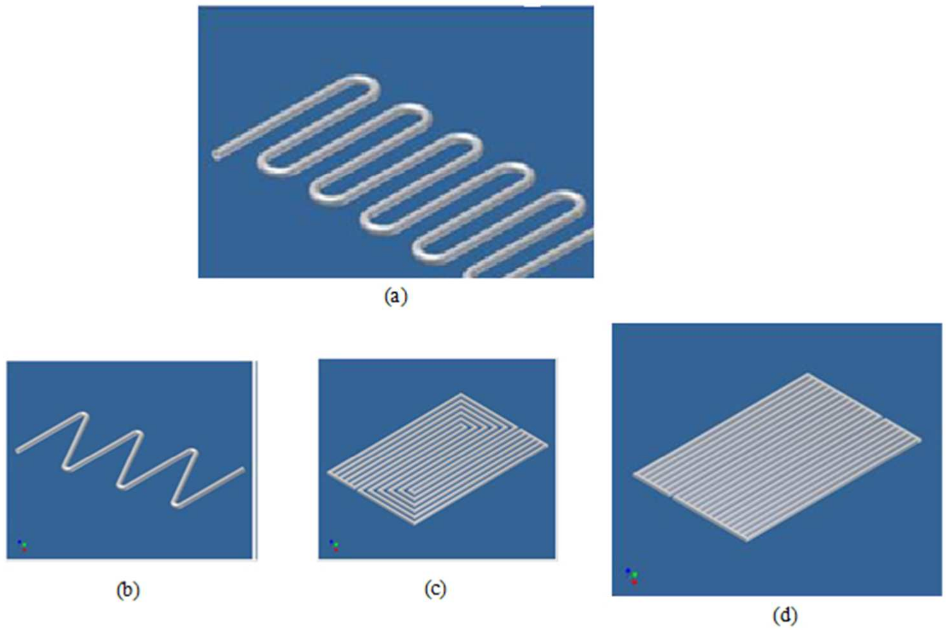

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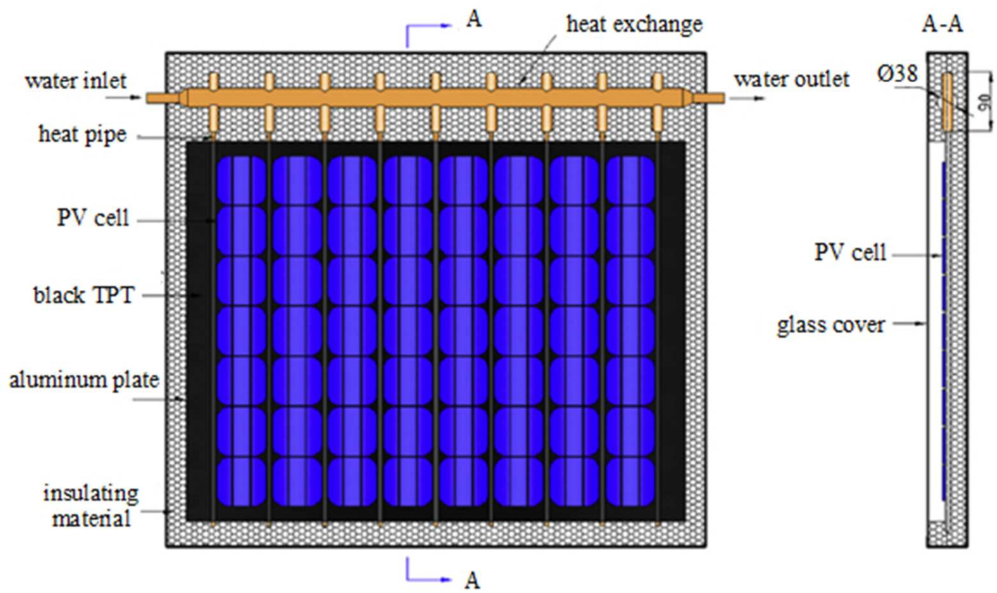
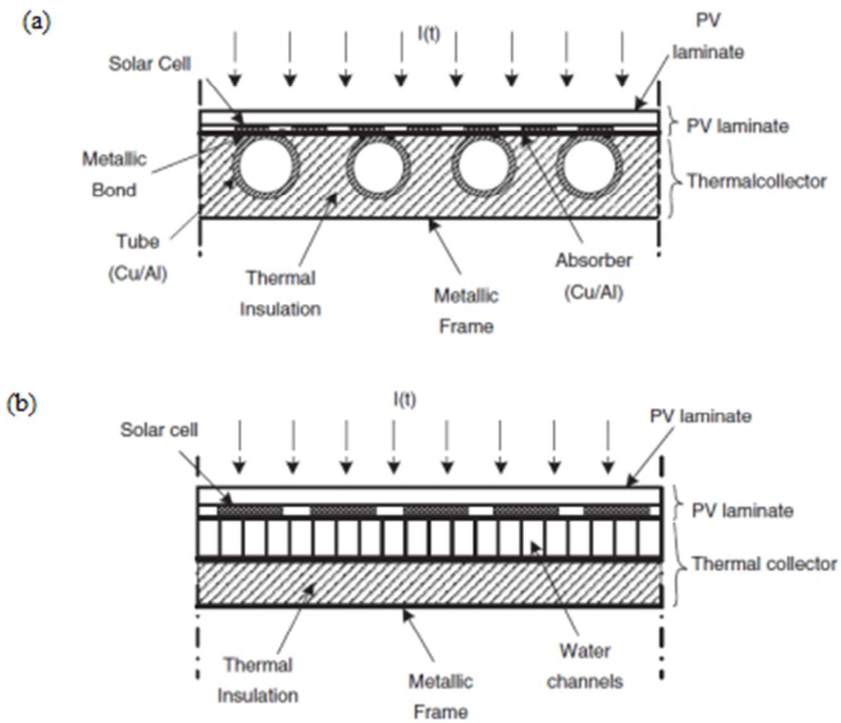
Review



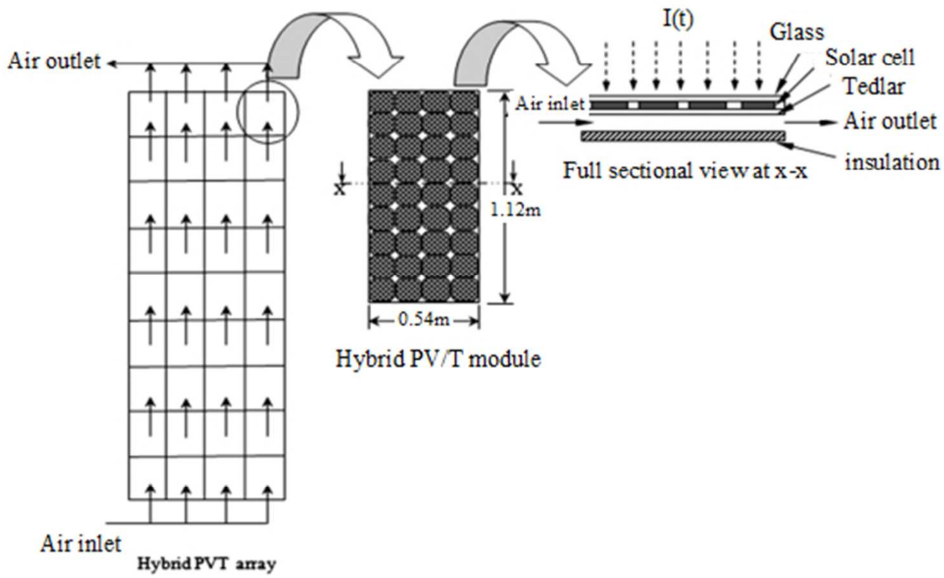
153x96mm (96 x 96 DPI)

r Review



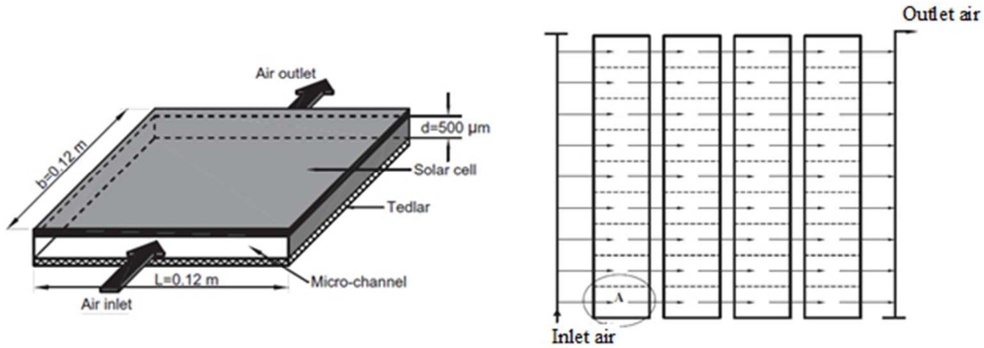
121x100mm (96 x 96 DPI)

review



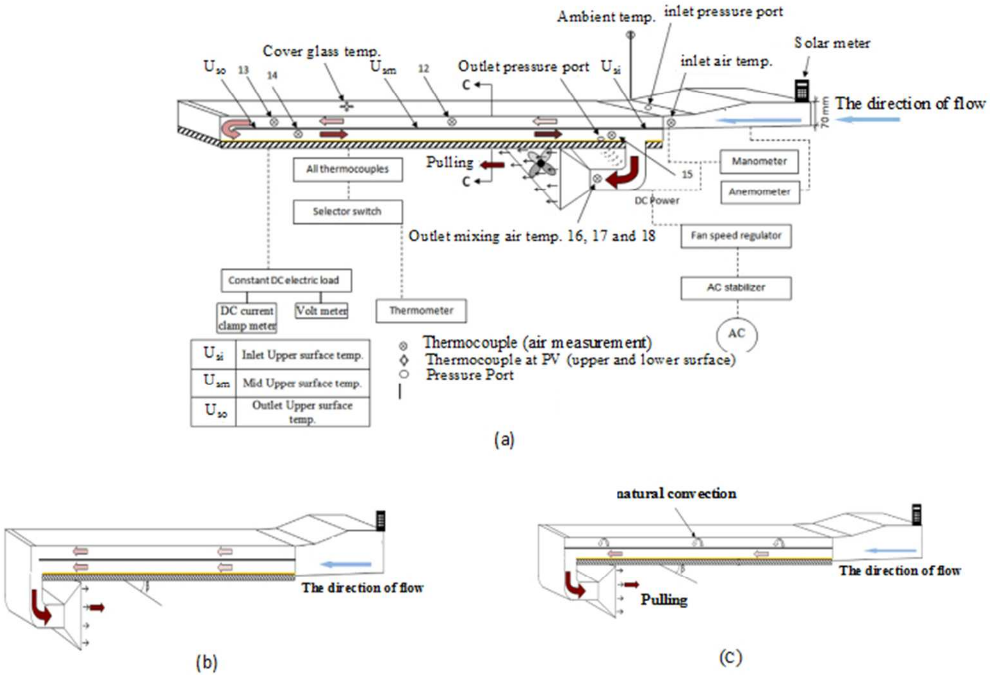
153x97mm (96 x 96 DPI)

r Review



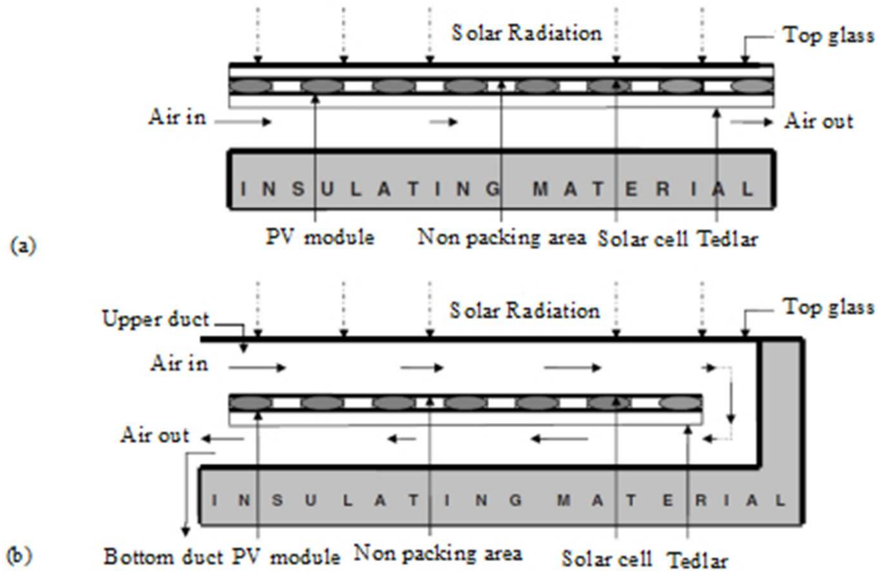
168x64mm (96 x 96 DPI)

For Peer Review



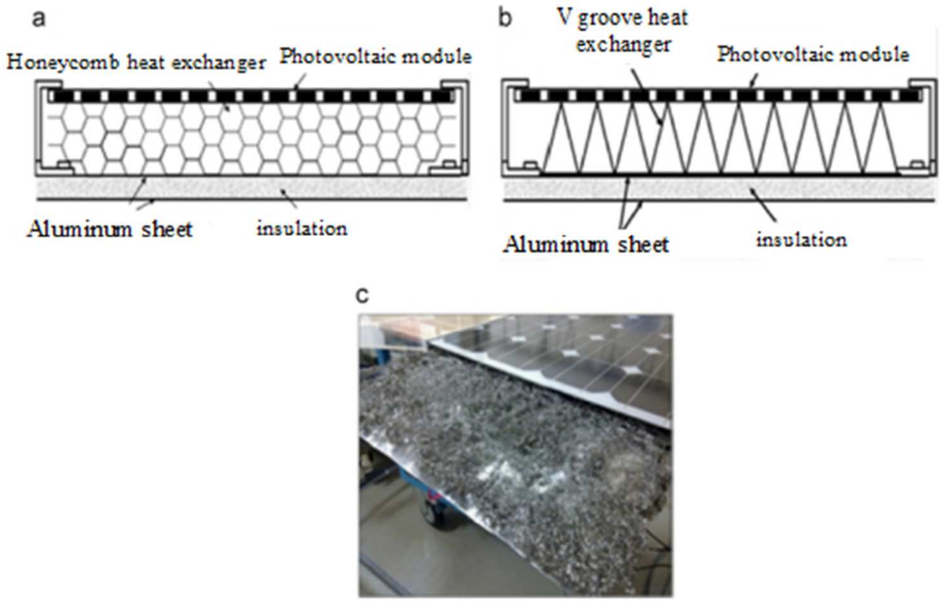
192x130mm (96 x 96 DPI)

Review



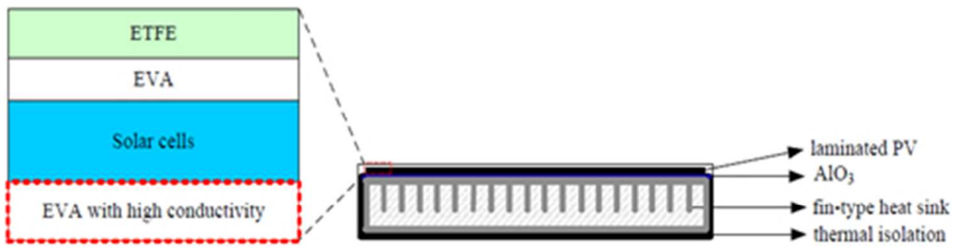
125x84mm (96 x 96 DPI)

Review



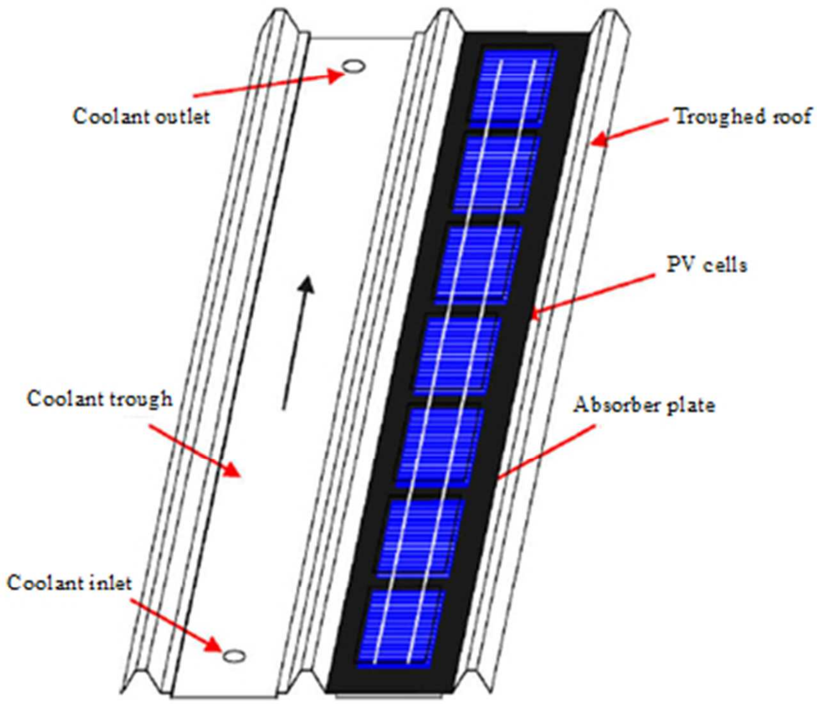
136x91mm (96 x 96 DPI)

Review



134x47mm (96 x 96 DPI)

For Peer Review



110x101mm (96 x 96 DPI)

Review